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Embedding complex hydrology in the climate system – towards fully coupled climate–hydrology models

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Abstract Motivated by the need to develop better tools to understand the impact of future management and climate change on water resources, we present a set of studies with the overall aim of developing a fully dynamic coupling between a comprehensive hydrological model, MIKE SHE, and a regional climate model, HIRHAM. The physics of the coupling is formulated using an energy-based SVAT (land surface) model while the numerical coupling exploits the OpenMI modelling interface. First, some investigations of the applicability of the SVAT model are presented, including our ability to characterise distributed parameters using satellite remote sensing. Secondly, field data are used to investigate the effects of model resolution and parameter scales for use in a coupled model. Finally, the development of the fully coupled climate-hydrology model is described and some of the challenges associated with coupling models for hydrological processes on sub-grid scales of the regional climate model are presented.

Key words

INTRODUCTION

To ensure the sustainable development of water resources it is important to understand the interactions between the atmosphere and the land surface and subsurface hydrology, and to be able to correctly represent these processes in our models. These interactions are not only crucial in assessing the renewable water resources under current conditions, but also for understanding the potential impacts of climate change on surface water and groundwater resources. At the same time, the effective management of water resources under stress requires the ability to represent interventions, such as operating river control structures or other processes including the conjunctive use of surface water and groundwater, and to evaluate how these might be used both under current conditions and for climate adaptation.

Making accurate predictions for climate change and adaptation in water resources is an immense task that can only be achieved through joint co-operation between scientists across the fields of hydrology and climate science. The work presented here has been motivated by the need to explore improvements in model descriptions of both the soil–vegetation–atmosphere transport (SVAT) processes in hydrology and the interactions between climate and hydrology.

SOIL VEGETATION ATMOSPHERE TRANSPORT IN A DISTRIBUTED HYDROLOGICAL MODEL

The results presented here build on the development and application of an energy-based SVAT (land-surface) model (Overgaard, 2005; Overgaard *et al*., 2007) as a component within the MIKE SHE modelling framework (Butts *et al*., 2004: Graham & Butts 2006). This component is based on the two-layer soil–canopy system of Shuttleworth & Wallace (1985) with some modifications to treat ponded water on the soil surface and water intercepted by vegetation (Overgaard, 2005). This energy-based Shuttleworth-Wallace type evapotranspiration (SWET) model was implemented within MIKE SHE to achieve a consistent coupling with atmospheric models (Overgaard, 2005). This development was also aimed at strengthening the link from remote sensing and hydrological modelling, making it possible to utilize some of the remote sensing (RS) data currently available more efficiently. The link between remote sensing and distributed hydrological modelling is important for integrated water resources management and provides the possibility to make more spatially detailed evaluations of hydrological simulations. The advantage of incorporating remote-sensing-based observations into the model evaluation process is their spatially distributed information content, enabling the assessment of the ability of the model to reproduce observed spatial patterns.

The SWET model has been evaluated at the plot scale and subsequently, using satellite data, including surface temperature, at the landscape scale (Overgaard, 2005; Overgaard *et al*., 2007). A detailed evaluation of the spatial distribution of the latent heat flux was obtained by including RS-based maps of radiometric surface temperature (RS surface temperature) in the evaluation procedure. Overall, the model was found to reproduce the spatial pattern of surface temperature well, although the model produced significantly less variation than observed in the RS surface temperature. The smaller variation was mainly attributed to the variability in soil, climate and land-surface properties not resolved by the model. Using this SWET component in a complex distributed MIKE SHE model for the 2500 km^2 Skjern River basin in western Denmark, Stisen *et al*. (2011) compare the use of conventional streamflow and groundwater head observations against distributed surface temperature data from satellite remote sensing for model calibration. They conclude that while observations such as stream discharge contain valuable information regarding the total catchment water budget, such traditional observations should be merged with independent data sets that incorporate spatial pattern information like remote sensing, to strengthen the robustness of model performance and constrain model parameters.

Ridler *et al.* (2012) present an investigation of combining remote sensing estimates of surface temperature and soil moisture *versus in situ* (point) for the calibration of this SWET model. Given that direct point observations of the fluxes and surface temperatures are generally scarce, it is of interest to know how well such a model can perform using other indirect data sources including remote sensing. A comparison of satellite-based surface temperature and soil moisture with *in situ* data, for these variables, is shown in Fig. 1 for a site in Mali. There is only a small bias and good correlation between the satellite and *in situ* measurements for surface temperature; however, the satellite data tend to over-estimate the soil moisture in this semi-arid soil.

Simulations indicate that the model is capable of simulating the surface temperature, fluxes and their dynamics, Fig. 2, for a single day. They also conclude that the combination of surface

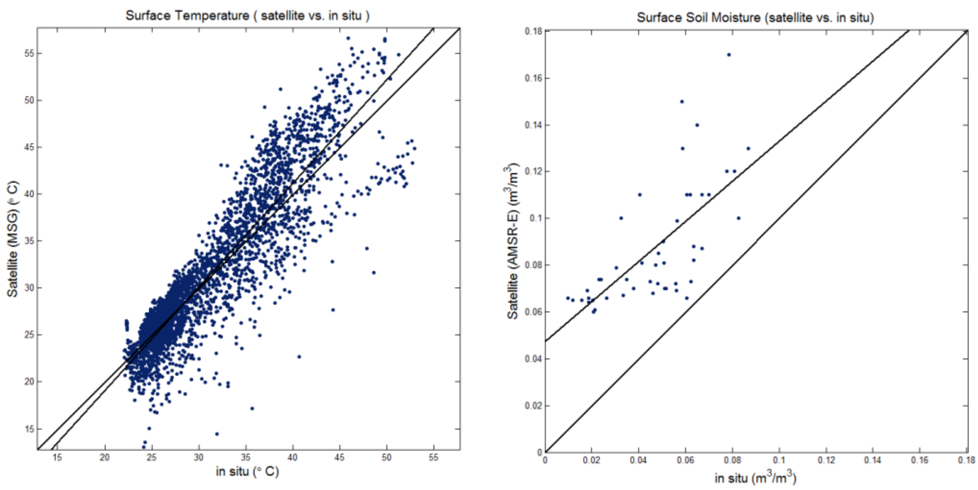

Fig. 1 A comparison of satellite (MSG) *versus in situ* observations of land surface temperature (left) and satellite (AMSR-E) *versus in situ* observations of soil surface moisture. Both data sets obtained for an arid site in Sahelian Mali during the 2007 growing season (Ridler *et al*., 2012).

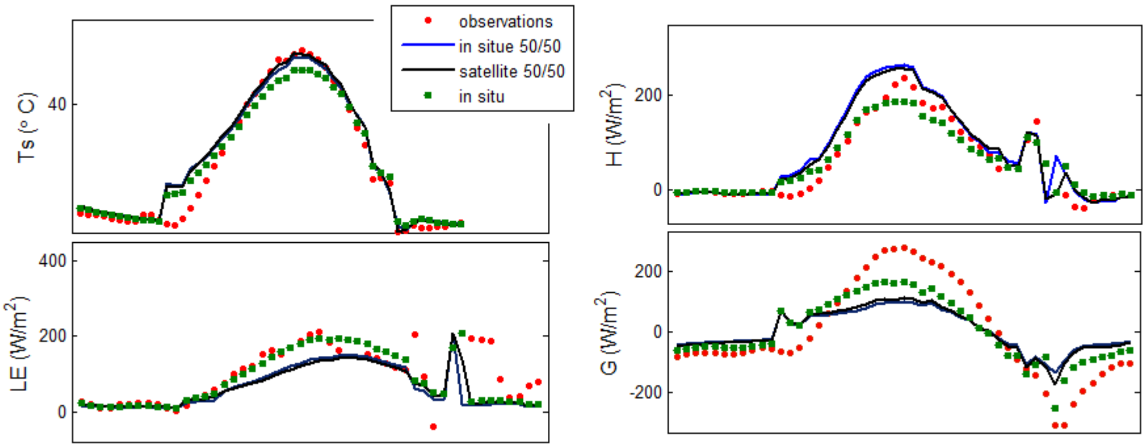

Fig. 2 Simulated and observed surface temperature (Ts) and flux (LE, H and G) for a single day. The red circles are *in situ* observations for each of these variables. The solid blue lines are simulations where the model is calibrated using an equal weighting of *in situ* Ts and soil moisture in the uppermost 5 cm of soil (θ_{05}) observations. The solid black lines are simulations where the model is calibrated using an equal weighting of the satellite Ts and θ_{05} objectives. The green squares denote simulation results where the model has been calibrated individually against each of the *in situ* observations of the variable of interest (Ts, LE, H, G) and is used as the calibration of objective. This represents the model benchmark performance.

temperature and soil moisture constrains many of the parameters important for flux modelling but with the important exception of the root depth, extinction coefficient and unstressed stomata resistance. The best estimates of flux are however obtained using in situ measurements of surface temperature and soil moisture as opposed to the satellite data (Ridler *et al*., 2012).

COUPLED CLIMATE–HYDROLOGY MODELLING

The primary motivation for developing this energy-based SWET component in MIKE SHE was to achieve a consistent coupling with atmospheric models (Overgaard, 2005; Overgaard *et al*., 2006). Conventionally, the hydrological impacts of climate change are assessed by driving hydrological models with output from downscaled regional or global climate models. This may have several drawbacks: first because the hydrological components within climate models focus mostly on the canopy and root zone while neglecting the interactions between groundwater, the root zone and surface water. This, in turn, may lead to poor predictions where groundwater and surface water are closely connected (Chen & Hu, 2004; Overgaard 2005). More importantly, however, the feedback between the two systems is neglected and this may potentially lead to inaccurate estimates of evapotranspiration (ET) (Rasmussen *et al*., 2012) and changes in hydrological and land use (Overgaard *et al*., 2005; Kim & Entekhabi, 1998).

One approach to address this limitation is to dynamically couple atmospheric and hydrological models. Such a coupled system can be used to investigate the interactions and feedback mechanisms and their significance for land-use and climate change studies. Overgaard *et al*. (2006, 2007) developed one of the first such dynamically coupled systems using the above energy-based SWET scheme to couple the MIKE SHE hydrological modelling system to the ARPS atmospheric model (Xue *et al*., 2001). Another novel aspect of this work is that it was one of the early applications of the concepts of the Open Modelling Interface (OpenMI) to achieve the dynamic coupling. OpenMI was originally developed within water resources modelling to allow coupling of existing models from different modelling groups by defining a standardised set of interfaces that the coupled models must comply with to allow data exchange during run time (Gregersen *et al*. 2007). Overgaard (2005) presents the physical and technical aspects of his coupling approach and carried out an evaluation of the coupling in a single column using data from the First ISLSCP Field Experiment (FIFE) in Kansas (Sellers *et al*., 1992). As shown in Fig. 3 the coupled model

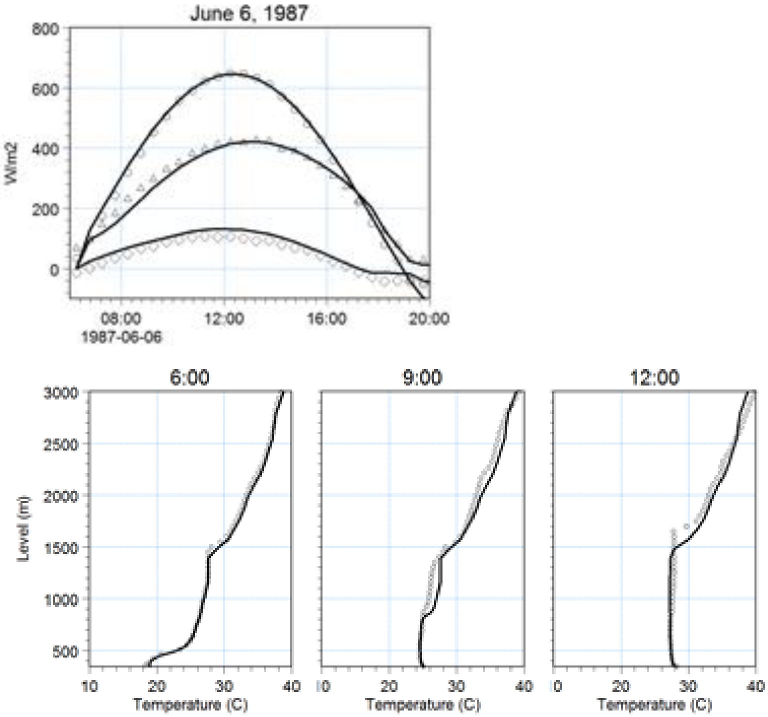

Fig. 3 Observed net radiation (circles), latent heat (triangles), and sensible heat (diamonds), and the simulated values (left) and the corresponding profiles of potential temperature in the lower 3000 m of the atmosphere for the same day, where the observations are shown as dots and the simulations as lines.

was able to accurately reproduce observations of the net radiation, latent and sensible heat and the profiles of potential temperature in the lower 3000 m of the atmosphere.

Using this coupled model for a single column, Overgaard (2005) investigated the influence of feedback on the sensitivity of latent heat fluxes to changes in key land-surface parameters. He found that the feedback can work both to dampen and to amplify sensitivity, depending on the parameter being perturbed. For example, when simply converting grassland to agricultural land-use, he found that neglecting feedback led to a 40% overestimation of the predicted change in evapotranspiration.

However, this early work examined the case of coupling in a single vertical column. The next step has therefore been to extend this work to distributed modelling over different sites. This has been part of the objectives within the HYACINTS project (www.hyacints.dk). One particular goal of this project has been to develop and apply a coupling between the HIRHAM regional climate model RCM (Christensen *et al.*, 2006) and the MIKE SHE hydrological model (Graham & Butts, 2005). One of the primary motivations of such a coupling has been to embed the comprehensive process-based hydrological modelling capabilities of MIKE SHE into the HIRHAM RCM. This allows a more detailed representation of both the surface and subsurface hydrological processes, as well as lateral movement of water in both the surface and the subsurface. Furthermore, the ultimate goal of the development of such a coupled modelling tool is not only to assess the impacts of climate change, but to evaluate climate-change adaptation measures and strategies in response to climate change. This requires models like MIKE SHE that are also able to represent interventions such as changes in land use, irrigation strategies or reservoir operations.

Several such coupled models have been developed (e.g. Seuffert *et al.*, 2002; York *et al.*, 2002; Overgaard *et al.*, 2007; Maxwell *et al.*, 2011) to investigate feedback processes and compare coupled and uncoupled simulations. However, there are a number of challenges remaining before we are able to effectively use such coupled models in practical cases. As pointed out by Rasmussen *et al.* (2012), many such simulations have been carried out where the atmospheric and hydrological models have been applied to the same domain at the same resolution. However, the relevant spatial scales for regional climate modelling and hydrological modelling are quite different. Therefore coupling of a higher-resolution hydrological model over the domain of hydrological interest within a large RCM domain using a coarser resolution may be more appropriate and also more computationally efficient. This enables better resolution of the local land–atmosphere feedback, including more detailed simulations of the soil vegetation processes using the hydrological model, while the meso-scale climate and land-surface processes outside the hydrological domain are described by the RCM's own land-surface scheme. To the authors' knowledge, no such two-way coupling has been reported in the literature. The concepts and protocols of Open MI were used to couple HIRHAM and MIKE SHE. Furthermore, this coupling is carried out across computing platforms, enabling the climate model to be run efficiently on the in-house supercomputer or Linux cluster, while the hydrological models can be run on one or more Window platforms.

COUPLING OF HYDROLOGICAL MODELS IN A LARGE-SCALE RCM DOMAIN

Within the HYACINTS project, coupled models where the hydrological models cover a smaller area within the RCM domain have been developed and are being applied to two case studies: the FIFE area in Kansas, USA, and the Skjern River basin in Denmark. To date, there appears to be only limited information in the literature that addresses related questions, such as what are the appropriate spatial and temporal scales that should be used in both the climate models and the hydrological models to ensure accurate simulations of the water and energy fluxes between the land and atmosphere. Rasmussen *et al.* (2012) investigated the effects of spatial resolution on the evapotranspiration and soil moisture for the FIFE catchment. Continuous simulations over an entire growing season were carried out for the FIFE domain at a range of grid sizes from 240 to 1500 m. They found that in this case that it is possible to use the distributed physically-based SWET model parameterised with field and literature data and simply upscale the evapotranspiration to RCM model scales by aggregating soil and vegetation data to 15-km grids. This is in some respects encouraging in that it suggests that high resolution coupled climate–hydrological modelling may not be important for estimating the large-scale evapotranspiration fluxes to the climate system. It should be recognised that the FIFE study area is a relatively homogeneous domain in terms of its hydrological characteristics and that for more heterogeneous areas this assumption may breakdown. However, an examination of the soil moisture and groundwater recharge showed much stronger effects. They are in agreement with other studies of the FIFE area that the soil moisture is much more sensitive to spatial resolution. More importantly, they found significant differences in the groundwater recharge which will have important implications for estimating changes in the overall water balance, available resource and sustainability of the estimated groundwater resource. Unfortunately, the FIFE study does not have groundwater observations to validate the recharge predictions.

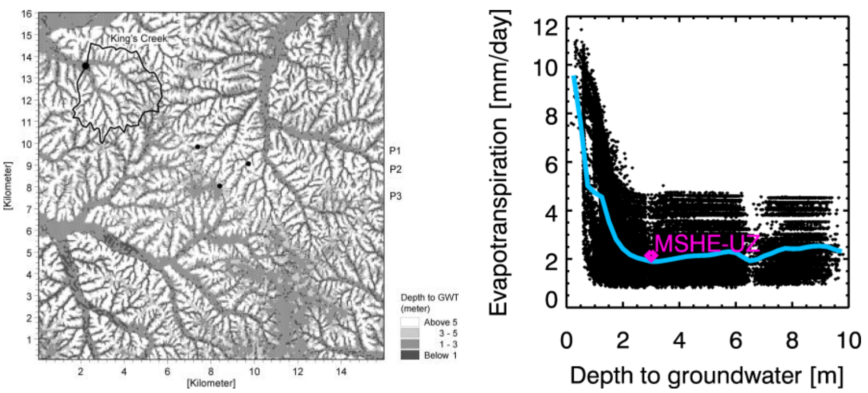

Fig. 4 Distribution of depth to groundwater over the FIFE model domain for a single day in May 1987 (left). The simulated variation of evapotranspiration versus groundwater depth, for all cells of soil type, Florence-Benfield, for a single day in August 1987. The solid line represents the variation assuming a constant depth to groundwater, (right). (Rasmussen *et al*., 2013).

Subsequent experiments using the hydrological model with and without dynamical groundwater (Rasmussen *et al*., 2013), show that including dynamical groundwater in the simulation is important for maintaining the high evapotranspiration rates observed during the driest part of the simulation period. This appears to be a result of different and more realistic evapotranspiration rates from areas with shallow groundwater tables. As might be expected the evapotranspiration rates depend strongly on the depth to the groundwater (Fig. 4). The ability to represent this type of hydrological variability within an RCM grid is likely to have important implications for coupled model simulations. This, together with the fact that the land surface scheme in the HIRHAM RCM is quite different from the MIKE SHE, suggests that we can expect significant differences in the results from the coupled model in comparison to the individual climate and hydrological models. This is clearly illustrated from some early results obtained over the Skjern River during the summer of 2009 (Larsen *et al*., 2012).

However, it should be recognised that the observations presented here in relation to coupled modelling have focused primarily on water and energy fluxes in a coupled climate–hydrology model. An even more challenging issue is the representation of precipitation at the proper scales. The approach adopted here, where the hydrological model forms part of the RCM model domain has the advantage that the meso-scale precipitation processes are captured at the appropriate scales, but some of the spatial variability in the precipitation may be lost depending on the resolution of the RCM and the dominant precipitation type (convective or frontal). Furthermore, the well-known biases in current climate model projections need to be addressed for these coupled models to be used for reliable climate projections.

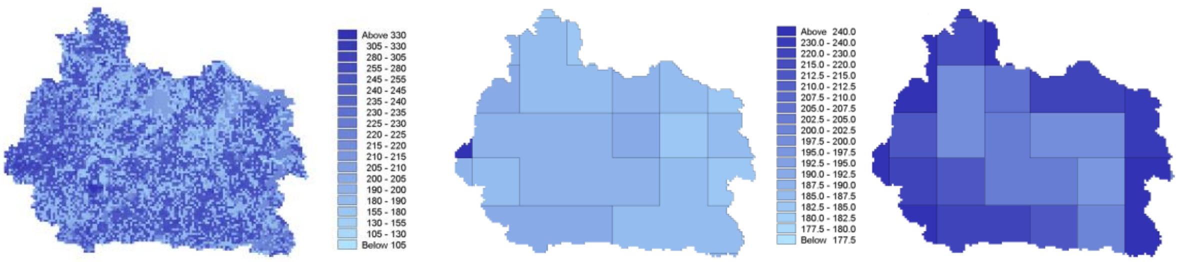

Fig. 5 Distribution of simulated evapotranspiration using MIKE SHE (left), HIRHAM RCM (middle) and coupled MIKE SHE–HIRHAM (right) for the Skjern River basin for the period June–August 2009.

CONCLUSIONS

This paper presents a brief overview of a long-term effort to develop an energy-based soil–vegetation–atmosphere for application to distributed hydrological modelling and coupled climate hydrological modelling. The resulting coupled models have been used to investigate the effects of feedbacks on the predictions of evapotranspiration, soil water and groundwater recharge. The results presented here suggest that the predictions resulting from coupled and uncoupled simulations can be significantly different in agreement with other studies. More recently, within the HYACINTS project, coupled models have been developed where the hydrological models cover a smaller area within the RCM domain. This work has highlighted the fact that there remains a number of challenging issues in relation to the scale and variability of both precipitation and evapotranspiration processes that require further investigation.

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